SHIP RISK MANAGEMENT AND STRUCTURAL RELIABILITY

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Abstract

US Navy Acquisition Reform is presented as a means of reducing costs and risks in the acquisition process, while providing improved mission performance for Navy assets. The 21st Century Destroyer Acquisition Program is an outgrowth of this desire, with the attainment of the US Navy's performance goals by new designs being demonstrated by commercial design teams instead of being based upon traditional, detailed military specifications. One role of the US Navy technical community will be to certify the design meets the program performance goals. Due to an absence of formal performance metrics, there may be unmitigated risks that the certification process will either approve an unacceptable design or reject an acceptable design. Both types of risk would negatively impact the US Navy acquisition process. This paper discusses the programmatic risk reductions inherent in adopting a technical risk-based approach, by identifying the role of reliability-based acceptance criteria for ship structures.

Introduction

US Navy Acquisition Reform is presented as a means of reducing costs and risks in the acquisition process, while providing improved mission performance for Navy assets. The21st Century Destroyer Acquisition Program is an outgrowth of this desire, with the stated intent of shifting the burden of meeting the US Navy performance requirements to the competitive environment of the commercial sector and away from traditional military specifications. The attainment of the US Navy's performance goals by new designs is to be demonstrated by commercial design teams. These teams are to develop the assumptions and tools necessary to support the use of performance metrics and their associated acceptability thresholds. A principal role of the US Navy technical community will be to certify the performance metric process and the conclusion of acceptability. Due to the absence of formal performance metrics, there remain unmitigated risks that the certification process will either approve an unacceptable design (consumer's risk) or reject an acceptable design (producer's risk). Both types of risk would negatively impact the US Navy acquisition process.

For the ship hull structure, a process has been developed to predict structural reliability: a formal, performance metric. Reliability is defined here as the probability that a structural failure mode will not occur for a specified design environment and lifetime. The product of the failure mode probability and the failure consequence, or cost, provides a measure of technical risk, or expected loss. A reliability-based, acceptability process allows use of currently available technologies to produce a formal and traceable risk or performance measure for each identified failure mode. This paper discusses the programmatic risk reductions inherent in adopting a technical risk-based approach, by identifying the role of reliability in the development of acceptability criteria for ship structures.

Risk Management

Risk management is a project management supporting methodology used to minimize the likelihood of events that may impede a program's success. These undesirable events constitute program risks. The act of reducing the impact and likelihood of program risks to acceptable levels is termed risk mitigation. *Continuous Risk Management Guidebook* (CRM) (Dorofee, et al, 1996) defines risk as the possibility of suffering loss. This qualitative definition is commensurate with program risk.

A second definition of risk is a measure of the probability and severity of adverse effects (e.g. Lowrance, 1976). This quantitative definition may be regarded as technical risk. The CRM Guidebook considers risk management as a management practice with processes, methods and tools for managing risks in a project. It provides a disciplined environment for proactive decision-making to: assess continually what could go wrong (risks); determine which risks are important to deal with; implement strategies to deal with those risks; and measure effectiveness of the implemented strategies. The measure of effectiveness is considered in the form of risk metrics. Metrics are used to: measure attributes of a risk; provide meaningful information to enable more informed control decisions; assess the impact of success of a mitigation plan; and identify new risks. Risk metrics can be measures based on technical performance, schedule, cost or other identified program quality. The first is commensurate with a measure of technical or probabilistic risk, while the others can be more appropriately considered as programmatic risk measures. From an acquisition perspective there are two general categories of risk: technical performance and programmatic. Programmatic risk refers to not meeting program schedules and budgets. Technical performance risk refers to not meeting the specified technical performance criteria. The degree to which technical performance is impaired is traditionally judged as a function of the design margins. Impact magnitude for technical performance may be considered as 1) minimal or no impact; 2) small with some reduction in design margin; 3) acceptable with significant reduction in design margin; 4) large, no remaining design margin; and 5) significant. The specification as to what constitutes an acceptable design margin has not been specified for the DD-21 acquisition.

Structural Reliability

Surface ships encounter a multitude of loads (e.g. wave bending, whipping, slamming) whose magnitudes and times of occurrence are highly uncertain. Some of these loads or combinations of loads are capable of damaging the ship's structure, possibly severely. Damage often results in a reduction or loss of structural integrity, or otherwise adversely affects ship system performance. Traditional design criteria attempt to guard against the possibility of structural damage and ship system degradation and failure by imposing deterministic safety factors into the design equations, tempered by engineering judgement. These safety factors, or design margins, have evolved over time and are highly correlated to the predictive tools and design domain for which they were established. The design margins are subjectively derived, quantitative evidence of the uncertainty inherent in design. Changes to either the tools or domain requires a change to the design margin. Unfortunately, with less reliance on engineering judgement, the traditional criteria often provide an undetermined level of safety and performance that experience has shown is not always adequate, even for traditional ship structural configurations. This inadequacy will only be heightened with the use of new design approaches beyond the traditional design domain, where implicit assumptions in the criteria no longer apply, and with the increasing demands of multiple, competing design and performance objectives as envisioned for future US Navy ships.

Criteria based upon explicit, first principles methodologies that incorporate structural reliability theory are an effective, formal and traceable manner in which to consider and create new designs. Structural reliability methods allow the prediction of occurrence likelihood for a particular event of interest (e.g. structural failure), allowing the designer to limit the probability of undesirable events. Calculating the probability that a failure event will not occur provides a performance measure termed reliability.

In reliability predictions of electronic or mechanical systems, much of the work has been carried out with the extensive use of failure databases which allow the prediction of the mean-time-to-failure (MTTF), mean-time-between-failures (MTBF), or failure rate, for each component of the system. Combining the failure rates of all the components to arrive at the system failure rate provides a means for finding the reliability of the system (Ayyub and McCuen, 1997; Kumamoto and Henley, 1996; Modarres, 1993). Studies such as Hawkins, et al. (1971), Jordan and Cochran (1978), Jordan and Knight (1979), and Akita (1982) provide the beginnings of a structural failure database for ship structures for use in this manner. Extensive testing of details for both fatigue and strength has provided a means by which the reliability of similar structural details may be predicted. This approach has lead to catalogues of structural details and members for use in design.

The extensive range of structural configurations and the large costs of testing at a statistically significant level have contributed to the development of structural reliability theory from an approximate "physics of failure" perspective. This approach propagates basic (input) variable uncertainty through an approximate model of the system under inspection, to provide the analyst with an estimated likelihood that the structural strength will be exceeded by the load, over the designated lifetime and under predetermined operating conditions.

Structural reliability theory has been developed with the assumption of crisp delineation of success and failure, and this approach has been carried into application to structural systems. The classical performance function is

$g = R - S$, where *R* represents the available resistance and *S* represents the load effect. The failure event is considered to be when g<0, or when the load, *S*, exceeds the resistance, *R* (Ang and Tang, 1990; Ayyub and McCuen, 1997; Thoft-Christensen and Baker, 1982; Madsen et al., 1986; White and Ayyub, 1985). This failure definition traditionally depends upon a resistance model that represents the ultimate strength of the structural component where the component is unable to carry any increase in load and is considered to have failed. Other non-strength related failure modes may also considered in this format, such as excessive vibration, deformation, or deflection.

The load and resistance are both represented by random variables that are functions of the ship's environment and structural geometry and material properties. The uncertainties in the strength and load basic variables and models have been discussed in Galambos and Ravindra (1978), Hess et al. (1994), Hess, et al. (1998), Hughes et al. (1994), Mansour and Faulkner (1973), Nikolaidis and Kaplan (1991), and White and Ayyub (1993). These basic variables require continued investigation to maintain accuracy over time and to decrease the uncertainty surrounding their probabilistic characterizations, particularly with the introduction of new materials, configurations and operation.

Traditionally, three methods are discussed and utilized in structural reliability predictions. These are referred to as Levels 1, 2 and 3, with complexity and amount of required information increasing with Level number (Madsen et al., 1986; Mansour, 1990).

Level 1 describes the use of design equations with partial safety factors developed using reliability techniques (Level II and III reliability methods). This approach is also termed Load and Resistance Factor Design (LRFD). The factors may also be developed without use of reliability methods and are an extension of the traditional, factor of safety design approach. The strength of the Level I approach is that the designer can efficiently utilize a reliability-based, LRFD code without potential errors resulting from the complexity of the higher-level reliability techniques. Reliability-based, LRFD codes are currently in use by the American Institute of Steel Construction (AISC, 1993), American Association of State Highway and Transportation Officials (AASHTO, 1998), American Petroleum Institute (API, 1993), and NORSOK (1998). Discussion of Level I methods and their development may be found in structural reliability texts and papers including Lee and Son (1989), Madsen et al. (1986), Mansour (1990), Thoft-Christensen and Baker (1982), White and Ayyub (1985).

Level 2 denotes approximate methods that utilize only the means and variances of variables in the limit state equation to predict the reliability and are termed First Order Reliability Methods (FORM). Extensions to FORM have been developed to allow approximate inclusion of the basic variable probability density functions. This modified approach is termed the Advanced Second Moment (ASM) method and can provide a substantial increase in accuracy. The reduction in needed information for a Level 2 reliability analysis makes it quite appealing and so it is frequently used. Level 2 methods are discussed in structural reliability texts and papers including Ang and Tang (1990), Ayyub and Haldar (1984a), Ayyub and McCuen (1997), Chao (1995), Der Kiureghian, Lin and Hwang (1987), Hasofer and Lind (1973), Madsen et al., (1986), Mansour (1990 and 1993), Modarres (1993) and White and Ayyub (1985).

Level 3 reliability assessment requires and utilizes complete probabilistic characterizations of all basic load and strength variables to capture the uncertainty inherent in the strength and the load predictions. A popular method of solving this problem is Monte Carlo simulation, as closed form solutions to the convolution integral are rarely possible. Efforts to improve the efficiency of Monte Carlo simulation include conditional expectation and antithetic variates variance reduction techniques (Ayyub and Haldar, 1984b), Latin Hypercube Sampling (Ayyub and Lai, 1989), and other techniques such as importance sampling as outlined in Ang and Tang (1990), Bjerager (1988), Casciati and Faravelli (1980), and Harbitz (1986).

The inclusion of technical risk in an analysis or design is informally considered Level 4 (Madsen, et al., 1986). To achieve this quantitatively, probability of occurrence must be attached to the failure event and the consequences corresponding to the failure must be identified and assigned some value. The technical risk measure would be the product of the probability of failure and the failure consequences.

The idea of calculating the technical risk, or expected loss, associated with a structural design, is to provide a normalized value that is transportable beyond the specific system, sub-system, or component under study for consideration in a larger context. For comparison or aggregation of structural sub-systems, a metric is needed. This metric may be found in the prediction of risk. The acceptable reliability levels associated with structural components throughout a structural system may not be constant, but could vary as the importance of the components vary. This importance may be measured by jointly considering the consequences and likelihood of component failures, thereby providing the technical risk associated with the component.

An example of structural failure is the permanent deformation of an unstiffened plate. Excessive permanent set may misalign some mechanical system rendering it inoperable; reduce the strength of a larger structural system beyond acceptable levels and endanger more critical systems; violate signature control restrictions; or be cosmetically unappealing. The consequence of the permanent deformation may also be an increase in the likelihood of greater system failures. The point at which the deformation level becomes unacceptable for the designer, owner or surveyor is the onset of failure for the plate. The failure definition for the permanent set of unstiffened plating is dependent upon the acceptability of the consequences of the permanent set. When the consequences are no longer acceptable, the plate has failed. A designer attempts to limit the likelihood of the plate experiencing such plastic deformation. The probability that the plate does not exceed some specified value of permanent set is the reliability. A criterion must be set for this failure mode. A deterministic criterion would enforce a limiting value on the permanent set, without considering any restriction on the probability of this limiting value being exceeded, nor addressing uncertainties in the calculation. In this case, the risk of failure would be unknown, though a design margin may be applied based on engineering judgement. An alternative approach would be to calculate the reliability associated with this failure mode for a specified level of permanent set and compare it to a technical risk-based, reliability criterion to judge design acceptability, formally and traceably accounting for uncertainties in the process.

Acceptability Criteria

A decision as to the acceptability or unacceptability of a system based on a risk or performance measure requires the setting of acceptance criteria. These criteria are threshold values that delineate between success and failure, or acceptable or unacceptable domains. Criteria are used for decisions regarding acceptance of new designs, changes to existing systems, or a means of ranking different options. Criteria may also provide elevated goals for designers, different than those used for acceptance, such that a more optimal design may result.

The traditional form of criteria is deterministic in nature. Deterministic criteria attempt to neutralize the influence of uncertainty by arriving at some safety margin, or factor of safety, which causes the designed system to show a much higher performance, or lower risk, than the threshold delineating acceptable and unacceptable domains. This is a simple approach allowing rapid design and analysis of systems. The drawbacks are the lack of clarity in all assumptions, and the inability to update the criteria with greater system knowledge. Deterministic approaches are founded in tradition and experience, and are useful for simple decision making, but assure an unknown level of safety.

Probabilistic criteria require explicit modeling of the system in question. The inclusion of uncertainties and dependencies are a means of addressing the uncertainty by modeling the likelihood of an undesirable event. This method requires an understanding of the risk-generating processes and can produce a quantitative or qualitative measure. The ability to update the process with new knowledge makes this technique preferable to deterministic techniques, but not everything is easy to quantify. The amount of information required for accurate results is much greater than for a traditional, deterministic approach.

Risk assessment requires the determination of potentially hazardous scenarios, the likelihood of the scenario and the associated consequences. The resulting measure of risk, or change in risk, may be considered the expected loss. This expected loss could then be compared to the governing criteria to decide acceptability. A performance-based assessment considers measures such as reliability, availability, maintainability, capability and efficiency.

Criteria are used for the decisions regarding the acceptability of a system such as in government regulation and must address issues such as:

- How safe is safe enough?
- Will this design perform to an acceptable level?
- Will this change to the existing system affect the system risk or performance in a significant manner?

When criteria are developed to be used for achieving a optimal design, the goal is not of a regulatory nature, but one of assuring that the needs of the customer are met. Such criteria assist the design management team in defining the performance/risk goals such that they do not limit the designers, nor significantly exceed the required levels of safety as prescribed by regulatory bodies.

Acceptability of a certain level of risk or performance requires the mapping of the decision maker's judgement and values into an expression which is comparable to a quantitative or qualitative measure of the system or process in question. The decision-maker represents the society and individuals that may be impacted by the decision. The measure may be considered either qualitative (subjective) or quantitative (objective). Qualitatively, the criteria must take into account the need for the risk exposure, the amount of dependable controls over the risk producing process, and the fairness in which the costs, risks and benefits are distributed (Reid, 1992). Quantitatively, the criteria must take into account uniformity of standards and efficiency (Reid, 1992). Modarres (1993) proposes that fair, balanced and consistent risk criteria must be based upon comparison of the risks and benefits associated with certain activities.

Strict quantitative criteria are in the risk or performance domain characterized by quantitative system analysis, which produces a measure with physical meaning. The risk is presented as an expected loss, calculated as the product of the frequency and consequences of the event. Such criteria are based on technical analysis, and do not necessarily address value judgements.

Absolute criteria are independent limiting values that reflect the world-view of the system analysts. Absolute criteria used for judging new systems provide a fixed bound for the acceptable domain. The absolute value predicted by the analysis is comparable to measures of other systems only if all uncertainties and contributors have been identified. The choice of "one-in-a-million" as the criterion governing acceptable risk is an example of an absolute quantitative limit without added conditions, whereas the "as-low-as-reasonably-possible" is a qualitative criterion without need for comparison.

By quantitatively assessing similar systems (which are deemed to represent acceptable risk levels) in the same context and matching new designs to the calculated levels, relative criteria may be developed. This is a calibration of the new tool to existing practice that has been popularized in structural reliability-based design code formulation. The coarseness of the structural system models requires a similar coarseness in the criteria. The result is a means of assuring that at least a certain level of risk, or failure probability, is not exceeded. These type of calibrated criteria, currently being developed by the US Navy, are reliability-based design guidelines embodied in a Load and Resistance, Factor Design (LRFD) format. LRFD criteria are analytical, closed form checking equations with partial safety factors developed through the use of Level 2 and 3 reliability methods such as Method of Moments and Monte Carlo simulation. These guidelines are being developed using current, US Navy load and strength prediction technologies and information, and consider only traditional structural materials and configurations for a limited range of structural failure modes. Though limited, they represent a significant shift in the manner of conducting designs and assessing design acceptability from traditional approaches and form a framework from which new ship structures and materials may be addressed. This work can be extended and expanded such that the structural risks associated with new US Navy ship acquisitions are mitigated, by quantitatively ensuring acceptable levels of safety and performance as compared to past experience.

Conclusion

The 21st Century Destroyer Acquisition Program represents a change from traditional acquisition and design of US Navy surface combatants leading to higher levels of risk and uncertainty. The DD-21 is being designed to operate at high speeds in severe environments for longer durations, carry increased payloads, be more survivable and have reduced acquisition and life-cycle costs. These goals require new technologies, loadings, materials and configurations that involve a large degree of risk and uncertainty in their implementation. The degree to which the stated performance goals are achieved is left to the commercial designer, while acceptance of the resulting design is the responsibility of the US Navy technical community. To minimize the risk of certifying an unacceptable design or rejecting an acceptable design, a metric and acceptability criteria is recommended that would consider performance goals and design margins in a reliability-based format. The reliability-based guidelines currently in development by the US Navy require extensions to encompass new structural failure modes, materials, configurations, and analysis technologies. Utilization of this new technology by industry designers working in collaboration with the Navy technical developers would create a reliability-based design and acceptability process in an efficient and effective manner. Rigorous and traceable consideration of all structural failure modes in a reliability framework allows formalized, quantitative risk-based decision making, effectively mitigating programmatic risks.

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